an earlier report by Newton[9] has suggested an assignment of 2− for this state. The experimental distribution $W(\theta)=1-0.175P_2(\cos\theta)$ may be fitted for either of the above assignments, but for the latter assignment only if one assumes that the compound state (2−) is formed exclusively by channel spin 2. Neither the 2− assignment nor this mode of formation can be reconciled with the elastic scattering data which require approximately equal contributions of the two entrance channels. An assignment of 5/2+ for the first excited state of Na^{23} is again in agreement with these parameters. This internal consistency leads one to suspect not only that the compound state at $E_p=1.460$ Mev is indeed a 3− state, but also that the 5/2+ assignment for Na^{23*} is certainly the most plausible of those suggested.

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PHYSICAL REVIEW VOLUME 104, NUMBER 4 NOVEMBER 15, 1956

Beta Decay of Tb^{161}†

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The radiations emitted in the beta decay of 7-day Tb^{161} have been studied with a 180°, 40-cm radius of curvature, shaped magnetic field spectrometer and a scintillation counter. Gamma-gamma coincidence measurements have also been made. The following transitions with multipolarities indicated were observed (energies in kev): 25.5($E1$), 48.9($M1$), 56.9($E1$, tentative), and 74.6($E1$). The following beta groups were also observed (energies in kev): 571, 522, 496, and 439. A level scheme incorporating these data is presented.

I. INTRODUCTION

TERBIUM-161 is a β^- emitter with a half-life of 7 days. The spin of Dy^{161}, the daughter, was determined to be 5/2 by Cooke and Park.[1] The end point of the beta spectrum was determined to be 0.5 Mev by absorption measurement.[2] Scharff-Goldhaber *et al.*[3] made a probable assignment of a 26-kev gamma ray to Tb^{161} based on proportional chamber results. Cork *et al.*[4] reported a single 49.0-kev gamma ray which was converted mainly in the L_I electron subshell and from this fact assigned an $M1$ multipolarity to the transition. This group postulated that the beta decay went to an excited state 49.0 kev above the ground state and was followed by an $M1$ transition to ground. The energy of this gamma ray was given as 48.8 kev by Jaffe[5] from curved crystal spectrometer measurements.

Recently, Barloutaud and Ballini[6] studied the decay of Tb^{161} using a scintillation spectrograph and coincidence techniques. They reported a gamma ray at ~75 kev, 45–45 kev γ-γ coincidences, and 45–75 kev γ-γ coincidences. The total β-spectrum end point was determined to be 550±10 kev, and the β spectrum in coincidence with the 75-kev gamma ray was reported to have the same "shape" and end point as the total β spectrum. This group also found coincidences between a β group and a 47–48 kev gamma ray. They proposed a level scheme in which two beta groups populate the first and second excited states, 75 kev and 125 kev above the ground state of Dy^{161}, respectively, with no beta decay directly to the ground state.

Temmer and Heydenburg have examined the levels observed from Coulomb excitation in natural dysprosium.[7] They feel that the first excited state, spin =7/2, of the Bohr and Mottelson unified model[8] rotational band of Dy^{161} and Dy^{163} lies ~76 kev above ground, and that the second rotational level, spin =9/2, lies ~166 kev above the ground state.

It seemed to be of interest to re-examine the decay of Tb^{161} since neither of the reported level schemes incorporated all of the experimental data.

II. EXPERIMENTAL PROCEDURE

The beta spectrum and conversion lines were measured in a high-resolution, 40-cm radius of curvature, 180°, shaped magnetic field spectrometer.[9] A specially designed end-window, loop-anode counter[10] was used for electron detection. This counter has a plateau of over 100 volts at a threshold of 950 volts with a slope of 1.5% rise per 100 volts increase. A thin Zapon window (cutoff=1.7 kev), supported on 56% trans-

† Supported by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission, and by a grant from the Research Corporation.
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[3] Scharff-Goldhaber, der Mateosian, McKeown, and Sunyar, Phys. Rev. **78**, 325 (1950) (A).
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[5] H. Jaffe, University of California Radiation Laboratory Report UCRL-2537, 1954 (unpublished).
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[9] L. M. Langer and C. S. Cook, Rev. Sci. Instr. **19**, 249 (1948).
[10] E. A. Plassman and L. M. Langer, Phys. Rev. **96**, 1593 (1954).

mission Lectromesh,[11] was used for the detection of the low-energy conversion electron lines. An unsupported Zapon window (cutoff <6 kev) was used for measuring the beta spectrum. The spectrometer was calibrated in terms of the well known conversion lines of Cs^{137}, Bi^{207}, and ThB (*F* and *I* lines).

The gamma-ray scintillation spectrum was studied with a $1\frac{3}{4}\times1$ inch NaI crystal on a Dumont 6292 photomultiplier, feeding into a nonoverloading amplifier. The differential pulse-height spectrum was recorded with a 10-channel analyzer.

Gamma-gamma coincidence measurements were made by using two NaI scintillators with their axes at about 30 degrees. A one-inch Pb block was used between the crystals to reduce possible scattering from one scintillator into the other. After non-overload amplification, the pulses from one crystal were passed through a single-channel differential pulse-height selector and then into a coincidence circuit. The pulses from the other scintillator, after non-overload amplification, were suitably delayed and then entered the coincidence circuit. The coincidence circuit was set for a resolving time of 0.5 microsecond. The coincidence output pulse was made to operate a gate to pass the pulse-height spectrum from the second crystal into a ten-channel analyzer.

III. SAMPLE PREPARATION

The Tb^{161} used in this study was produced by the slow neutron capture of Gd^{160} and subsequent β decay of the 3.5-minute Gd^{161} to Tb^{161}. It was desireable to have a minimum amount of Tb^{159}, natural terbium, present which would produce the 75-day β emitter Tb^{160} by slow-neutron capture; this capture cross section is much larger than that of Gd^{160}. Approximately 5 mg of high-purity natural gadolinium was further purified by making an ion-exchange column separation using Dowex-50 cation-exchange resin with lactic acid as an eluant.[12] The gadolinium oxide was irradiated in the Materials Testing Reactor. The oxide was dissolved in concentrated hydrochloric acid and concentrated ammonium hydroxide was added to precipitate $Gd(OH)_3$. The hydroxide was dissolved in a minimum amount of 0.5*M* hydrochloric acid and the rare earth components were separated by elution from Dowex-50 cation-exchange resin with α-hydroxy isobutyric acid as the eluant.[13] The terbium fraction was made 0.5*M* in HCl and placed on a Dowex-50 cation-exchange resin column. The organic acid eluant was washed through the column with 0.5*M* HCl and then the terbium was removed by using 6*M* HCl as an eluant. This solution was evaporated to dryness and the activity was taken up in water. The terbium was deposited from this aqueous solution on a 980 $\mu g/cm^2$ aluminized Mylar film with the use of insulin to define the source area.[14] The source was then covered with a thin (less than 10 $\mu g/cm^2$) Zapon film to prevent possible contamination of the spectrometer vacuum chamber.

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[12] W. E. Nervik, J. Phys. Chem. **59**, 690 (1955).
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TABLE I. Conversion electron data.

Electron energy (kev)	Subshell or shell	Transition energy (kev)	Relative intensity
(16.5)[a]	L_I	(25.5)[a]	1.6[a]
(17.0)[a]	L_{II}	(25.5)[a]	1.2[a]
17.7	L_{III}	25.5	1.8
20.8	K	74.6	0.6
24.1	M	25.8(M_{III})	1.5
25.7	N	26.0(N_{III})	0.2
39.8	L_I	48.9	8.4
40.3	L_{II}	48.9	very small
41.0	L_{III}	48.8	very small
47.0	M	49.0(M_I)	2.1
46.6	N	49.0(N_I)	0.8
49.1	L	56.9(L_{III})[b]	...[c]
55.1	M	56.8(M_{III})[b]	0.1
56.7	N	57.0(N_{III})[b]	
66.6	L	74.4(L_{III})[d]	0.1

[a] See text, Part IV.
[b] Multipolarity tentatively determined to be *E*1; therefore one expects relatively large L_{III}, M_{III}, and N_{III} conversion.
[c] *L* line(s) partially masked by *M* and *N* lines of 48.9-kev transition.
[d] Multipolarity determined to be *E*1; therefore one expects relatively large L_{III} conversion.

IV. RESULTS

The conversion electron spectrum of Tb^{161} is shown in Fig. 1. A summary of the conversion electron data is given in Table I. The *L*-subshell lines of the 25.5-kev transition were resolved as follows. The transition energy was obtained by an extrapolation of the high energy edge of the L_{III} line. The L_{II} electron binding energy was subtracted from the transition energy and it was assumed that the L_{II} line intensity was zero at this point, e.g., all of the observed electrons at this energy were due to L_{III} subshell conversion. The spectrometer resolution of the L_{III} could then be obtained and the entire L_{III} was constructed with a shape similar to that of the 48.9-kev L_I line. The constructed L_{III} line was subtracted from the total and the L_{II} line was constructed with a shape similar to that of the L_{III} line. The L_{II} line was subtracted from the difference of the total and the L_{III} line and the L_I remained. The fact that the shape of the L_I line closely resembles the L_{III} line shape probably indicates that this method of resolution is reasonably accurate.

Three peaks were observed with the scintillation spectrometer. The energies were ~25, ~50, and ~75 kev. The 50-kev peak was broad and only partially resolved. It presumably contained at least three components: ~45-kev x-rays, ~50-kev gamma (predominant), and ~55-kev gamma.

The gamma-gamma coincidence studies showed an ~50-kev gamma ray in coincidence with an ~25-kev gamma (the latter was used as the gate). Using the 75-kev gamma ray as the gate an ~50-kev gamma was

[14] L. M. Langer, Rev. Sci. Instr. **20**, 216 (1949).

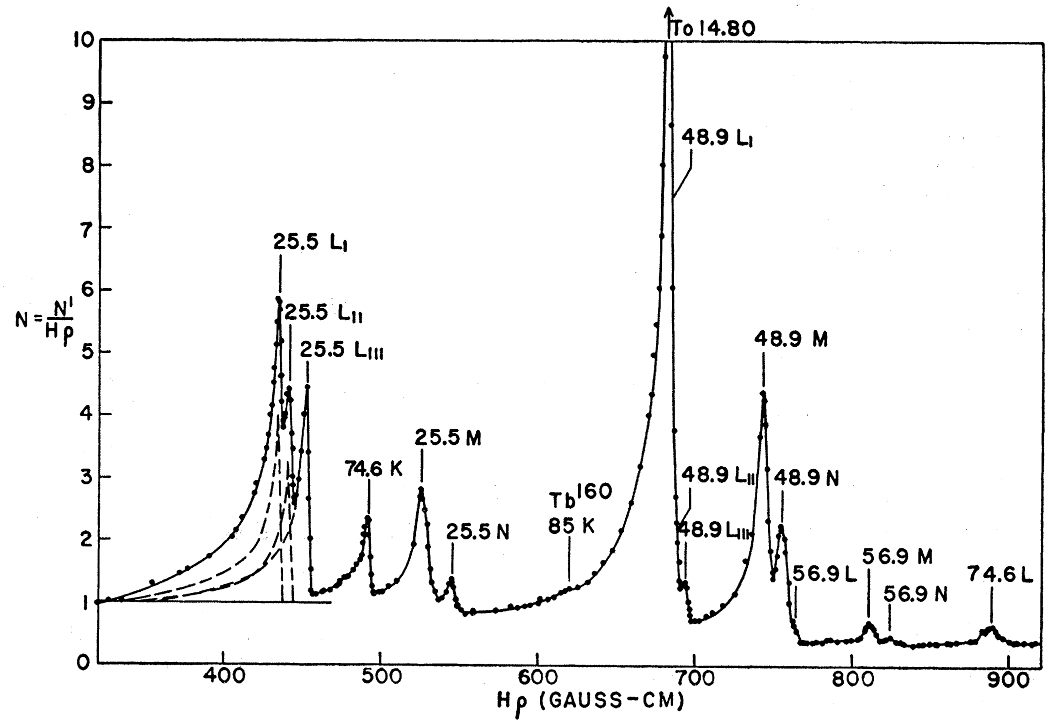

FIG. 1. The internal conversion electron spectrum of Tb^{161}.

found to be in coincidence. In the latter case, the energy of the peak in coincidence appeared to be slightly higher than it was with the 25-kev gate.

The energy sum of the 48.9-kev transition and the 25.5-kev transition, 74.4 kev, agrees within the experimental error with the energy of the 74.6-kev transition. These energies were obtained from the L_I, L_{III}, and K conversion lines, respectively. The order of emission is not evident at this point.

The following multipolarities were assigned on the basis of the unscreened K-shell conversion coefficients of Rose *et al.*,[15] and the privately circulated L-shell conversion coefficients of Rose, Goertzel, and Swift.

The 48.9-kev transition converts very largely in the L_I subshell which indicates that this is an $M1$ transition, in agreement with the assignment of Cork *et al.*[4] The amount of $E2$ mixing is probably less than 1%. The theoretical total L conversion coefficient ($M1$) is 2.3.

If the L conversion coefficient, L conversion electron intensity and gamma-ray intensity of one transition are known, the L conversion coefficient of a second transition can be calculated when the L conversion electron and gamma-ray intensities of the latter are known. The L conversion coefficients of the 25.5, 56.9, and 74.6 kev transitions were determined in this manner. It should be noted that the gamma-ray peak at $\sim$50 kev contained not only 48.9-kev gamma rays but also 56.9-kev gamma rays and $\sim$45-kev x-rays. It was assumed that the contribution of the two latter components was relatively small and their subtraction would decrease all of the other conversion coefficients which would not affect the multipolarity interpretations ($E1$ in all three cases).

The total L conversion coefficient for the 25.5-kev transition was found to be 2.1; the theoretical $E1$ coefficient is 1.9. The smallest theoretical coefficient, $M1$, excepting the $E1$, is a factor of ten greater than the experimental value. After resolving the L subshell lines, as earlier described, the $L_I/L_{II}/L_{III}$ ratios $=1/0.75/1.1$; the theoretical subshell ratios for an $E1$ transition$=1/0.70/1.1$. This is in agreement with an $E1$ assignment on the basis of the total L-conversion coefficient.

The L lines of the 56.9-kev transition are partially masked by the intense M and N lines of the 48.9-kev transition. The ratios $L/(M+N)$ for the 25.5-kev and 48.9-kev transitions ($E1$ and $M1$, respectively) are $\sim$3. It has been shown[16–18] that approximately the same ratio is found in several $E1$ and $E2$ transuranium element transitions. (No theoretical calculations are available for M and N shell internal conversion.) It was also shown in the latter cases that for a given transition internal conversion ratios in the M and N subshells are approximately the same as the L subshell ratios, e.g., $L_I/L_{II}/L_{III}\sim M_I/M_{II}/M_{III}\sim N_I/N_{II}/N_{III}$.

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[16] W. G. Smith and J. M. Hollander, Phys. Rev. **101**, 746 (1956).

[17] Hollander, Smith, and Mihelich, Phys. Rev. **102**, 740 (1956).

[18] Hollander, Smith, and Rasmussen, Phys. Rev. **102**, 1372 (1956).

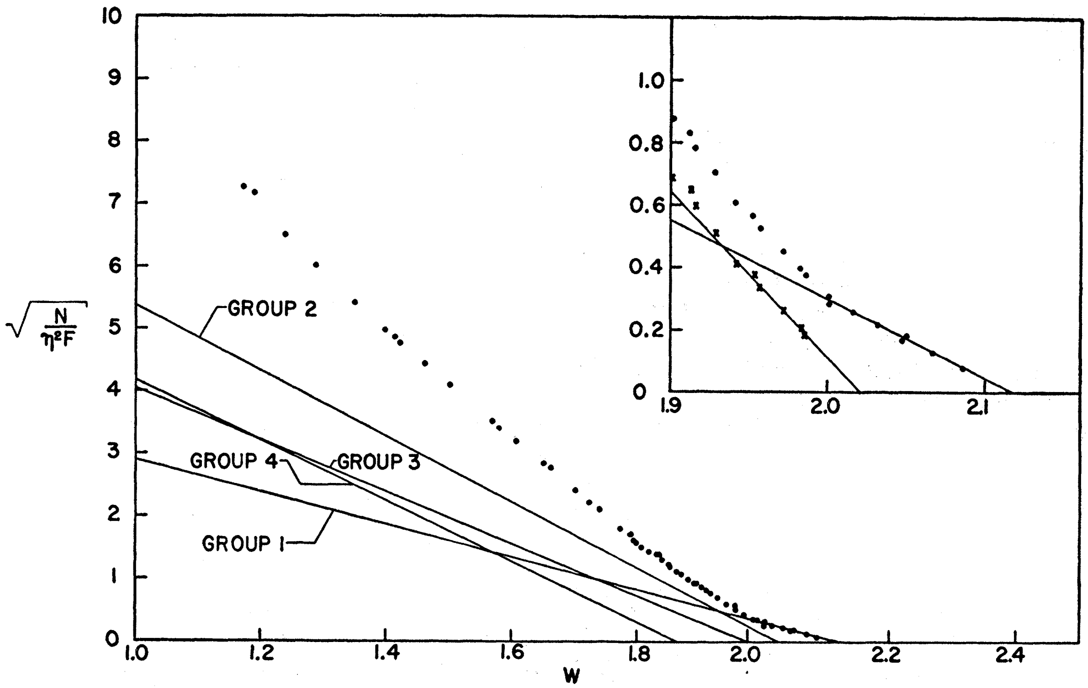

FIG. 2. Fermi-Kurie plot of the beta spectrum of Tb^{161}.

If one assumes that the same $L/(M+N)$ ratio prevails for the 56.9-kev transition, the total L conversion coefficient can be calculated from the beta-group intensity to this level (see following section) and the conversion electron intensities. This yields a value of 0.15 which agrees within the experimental error with the theoretical value of 0.21 for an $E1$ transition. The experimental value disagrees by approximately a factor of three (too small) with the theoretical value for an $M1$. The energy for this transition was determined by adding L_{III}, M_{III}, and N_{III} subshell binding energies to the respective electron groups. This assumes that an $E1$ transition is substantially converted in the M_{III} and N_{III} subshells. The two electron groups interpreted as M and N groups of a 56.9-kev transition might possibly be L_I and L_{III} groups of a transition with an energy of $\sim$64.4 kev. However, this interpretation gives a poorer internal energy consistency and the experimental total L conversion coefficient is a factor of four smaller than the smallest ($E1$) theoretical coefficient.

The K/L ratio for the 74.6-kev transition was found experimentally to be $\sim$7. The theoretical K/L ratios for $E1$, $M1$, and $M2$ transitions are 5.5, 6.0, and 3.1, respectively. The experimental total L conversion coefficient was determined to be 0.064. This agrees reasonably well with the theoretical value for an $E1$ transition which is 0.088; the experimental result disagrees by a factor of ten or more with any other theoretical coefficient.

There appears to be, on the low-energy tail of the 74.6-kev K line, a low-intensity L group of a transition of approximately 28 kev. This group is probably not a K line since no corresponding L lines are observed. The 25.5-kev transition has been assigned an $E1$ multipolarity; therefore any contribution to the gamma intensity by the 28-kev transition would be small.

The transition intensities, electrons plus gamma rays, were calculated using the theoretical conversion coefficients of Rose *et al.* and the experimentally determined multipolarities. The results are given in Table II.

The beta spectrum is complex and the transition energies obtained from the conversion electron and gamma-counting data aided in the resolution.

The resolved Fermi plots are shown in Fig. 2. Groups 1, 2, 3, and 4, in order of decreasing energies, have the following end points: 571±4, 522, 496, and 439 kev, respectively. The relative intensities (expressed in the same units as the conversion electron intensities) are: 2.6, 7.6, 4.2, and 3.9. The respective logft values are: 7.1, 7.2, 7.0, and 7.5. There was no indication that any of the beta groups had nonstatistical shapes; however

TABLE II. Transition data.

Transition energy (kev)	Total electron intensity (relative)	Multi-polarity	Theoretical conversion coefficient	Transition intensity electrons plus gamma rays
25.5±0.1	6.3	$E1$	1.9(total L)	8.7
48.9±0.1	12	$M1$	2.3(total L)	15
56.9±0.4		$E1$[a]		3.9[b]
74.6±0.4	0.6	$E1$	0.48(K)	1.8

[a] See Part IV regarding assignment.
[b] Obtained from resolved beta spectrum.

this possibility cannot be eliminated since the spectrum was complex and the end points were quite similar.

V. DISCUSSION

The agreement of the energy sum of the 25.5-kev and 48.9-kev transitions with the energy of the 74.6-kev transition indicates that the former are in cascade and the latter is a crossover. The intensity of the 48.9-kev transition is approximately twice that of the 25.5 kev; therefore the former must be the lower transition in the cascade, giving rise to levels at 48.9 and 74.6 kev. This is consistent with the beta-spectrum analysis if one assumes that the highest energy beta group, 571 kev, goes to the ground state of Dy^{161}.

The fourth beta group is separated from the third by $\sim$60 kev; because a 56.9-kev transition is observed it appears that the third excited state is at 131.5 kev above the ground state. The proposed level scheme is shown in Fig. 3.

The internal consistency of this scheme can be checked partially by comparing the incoming and outgoing populations of the levels.

The presently proposed level scheme was anticipated earlier in order to calculate the internal conversion coefficient of the 56.9-kev transition. Therefore, no check can be made on this level.

The relative ingoing intensity of the 74.6-kev level is 8.1, with 10.5 leaving. This is a reasonable agreement considering the uncertainties in the intensity measurements involved. There is an intensity of 16 going into the 48.9-kev level and 15 leaving, which is in good agreement.[19,20]

These data define four levels in Dy^{161}. As noted earlier, the measured spin of Dy^{161} is 5/2. Dy^{161} is between the closed neutron shells at 82 and 126, and the unified model of Bohr and Mottelson[8] might be expected to be valid in this region. The level calculations of Mottelson and Nilsson[21] predict that Dy^{161} should have a ground state spin of 5/2 (derived from an $f_{7/2}$ single-particle level) with negative parity. The first excited states of most nearby odd isotopes are approximately 80 kev above ground.[22] The unified model predicts that the ratio of the energies of the second excited rotational level, spin=9/2, to the first excited rotational level, spin=7/2, will be 2.3, for a nucleus with ground state spin=5/2. It was noted earlier that Temmer and Heydenburg[7] feel that they have observed these levels from Coulomb excitation, since they observed gamma rays at $\sim$76 kev and $\sim$166 kev.

The first excited state (48.9 kev) of Dy^{161} is depopulated by an $M1$ transition to the $5/2-$ ground state. This requires the former to have spin 3/2, 5/2, or 7/2, negative parity. It is not inconsistent with the $M1$ multipolarity assignment for this excited level to be a member of a rotational band with base spin 5/2. There appear to be at least two arguments against this interpretation. First, the energy is approximately 30 kev lower than that of the first excited members of rotational bands of most nearby isotopes.[22] Second, the gamma transition intensity rules of Alaga, Alder, Bohr, and Mottelson[23] predict the relative reduced gamma transition probabilities from a given level to members of a rotational band; the intensity ratio of the 25.5-kev

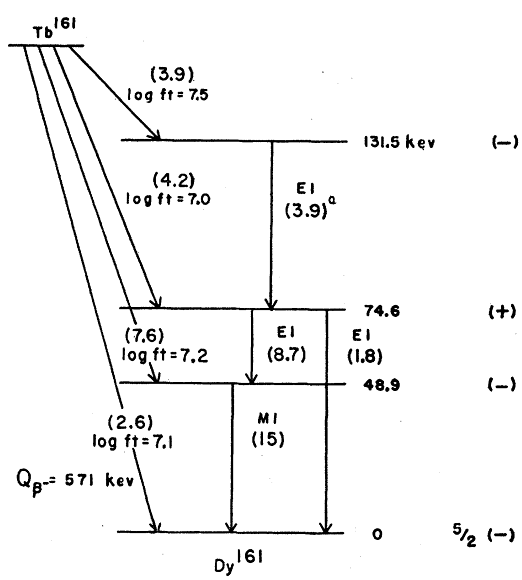

FIG. 3. Level scheme of Dy^{161}. Numbers in parentheses are relative intensities. The superscript "a" indicates transition intensity deduced from beta group.

[19] After this work was completed we learned of the recent results of Cork, Brice, Schmid, and Helmer[20] who have also studied the decay of Tb^{161}. They have proposed a scheme with levels at 25.6, 74.8, 104.0, and 132 kev, and report the maximum energy of the beta spectrum to be 540 kev. Our data do not appear to be entirely in agreement with this scheme; we find the 48.9-kev transition to be approximately twice as intense as the 25.5-kev transition which indicates that the former is the lower transition in the cascade. Also we obtain a beta-spectrum end point of 571 kev and find the second beta group to be $\sim$50 kev lower in energy than the first; it does not appear that this second group is either 25 or 75 kev lower in energy than first as would be required if the first excited state is 25 kev above the ground state. We had noted the existence of a low-intensity group of an $\sim$28 kev transition but were unable to fit it into our scheme. On rechecking our data, we find some evidence (very weak K and L conversion lines) for a transition of $\sim$104 kev. This could be a transition from the 104-kev level proposed by Cork *et al.*[20] to ground. The energy appears to be less than 106 kev. We did not observe any conversion electrons from a 78.3-kev transition. A small contribution of 78.3-kev gamma rays would not have been observed in the large 74.6-kev scintillation peak. These data indicate that there are levels at 104 and 49 kev but not at 25 kev. We did not observe the 132.1-kev transition; however, the K conversion line (if small) could have been hidden under the weak L conversion line(s) of an 85-kev transition in the decay of Tb^{160} which was present to a slight extent as an impurity.

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[21] B. R. Mottelson and S. G. Nilsson, Phys. Rev. **99**, 1615 (1955).

[22] A. Bohr and B. R. Mottelson, *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), p. 492.

[23] Alaga, Alder, Bohr, and Mottelson, Kgl. Danske Videnskab. Selskab, Mat.-fys. Medd. **29**, No. 9 (1955).

$E1$ to the 74.6-kev $E1$ is much larger than predicted by the rules if one makes assumptions for the spin and K quantum numbers of the 74.6-kev level.

The spin of the first excited state can only be stated as 3/2, 5/2, or 7/2 from the experimental data, the spins of the second and third excited states are similarly left undefined. The parity of the second excited level would be positive since it is depopulated to two negative parity levels by $E1$ transitions. A tentative $E1$ multipolarity assignment has been made to the 56.9-kev transition. If this is correct the parity of the third excited state is negative.

Mottelson and Nilsson[21] predict a spin of 3/2 or 5/2 with positive parity for Tb^{159}; the spin was experimentally determined to be 3/2. The spin of Tb^{161} could reasonably be expected to be 3/2; this interpretation allows an explanation for the nonappearance of the first excited rotational level in Dy^{161}, spin$=7/2$, since a spin change of 2 for the β transition would be required. This argument requires that the spin of the negative-parity states be $\leq 5/2$.

The fact that the $\log ft$ values for all of the beta groups are ~ 7 probably indicates that the group to the positive-parity level is allowed and is being hindered by some additional selection rule while the other groups are first-forbidden with spin change 0 or 1.

It appears that the level spectra of Mottelson and Nilsson[21] do not give a simple interpretation for the levels observed in Dy^{161}.

VI. ACKNOWLEDGMENTS

It is a pleasure to acknowledge the invaluable assistance and cooperation in the procurement of the Tb^{161} used in this study by the following members of the University of California Radiation Laboratory Chemistry Group: G. T. Seaborg, E. K. Hyde, J. M. Hollander, D. R. Nethaway, G. R. Choppin, and B. G. Harvey. We would also like to thank Professor E. J. Konopinski for his helpful comments.

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Fast-Neutron Cross Sections of Ge, As, Se, and Br

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The total cross sections of Ge and Se were measured for neutron energies between 60 and 650 kev, and those of As and Br in the energy range from 60 to 3000 kev. A comparison with calculated values is made.

THE giant resonances in the fast-neutron total cross sections[1] have been qualitatively accounted for by the complex square well model proposed by Feshbach, Porter, and Weisskopf.[2] This model does not predict, however, the polarization in the scattering observed by Adair and others.[3,4] For 400-kev neutrons the maximum polarization occurs for $A=110$ where the complex square well model predicts a P-wave giant resonance. Adding to the complex square well potential a spin-orbit coupling term[3] results in predicted polarizations which have a maximum near the observed values of A. The spin-orbit term, however, produces a splitting in the giant resonances for which no evidence has been found in the total cross-section measurements, as will be seen below. In the region of the P-wave giant resonance near 400 kev and $A\approx 100$ for which there is the most experimental information on polarization, data on total cross sections are rather incomplete. It was the purpose of the present experiments to fill this gap. At the same time, the measurements were extended over the whole energy range which had previously not been studied.

The experimental method was the same as in previous measurements.[5] Neutrons for the energy region from 60 to about 650 kev were obtained from the $Li(p,n)$ reaction; the higher energy range to about 3 Mev was covered by the $T(p,n)$ reaction. The neutrons were detected by a γ-ray insensitive hydrogen-filled recoil counter.

Total cross sections were measured for Ge, As, Se, and Br, corresponding to values of nuclear radius of approximately 6.0×10^{-13} to 6.3×10^{-13} cm. The arsenic, purified by resublimation under nitrogen[6] and packed in gas-tight containers 4.6 and 6.4 cm long and 1.9 cm in diameter under a nitrogen atmosphere, was checked for oxygen contamination by a study of the sample's neutron transmission in the neighborhood of the 440-kev resonance in the oxygen total cross section. No effect of the oxygen resonance was observed when a 10-kev

* Work supported by the U. S. Atomic Energy Commission and by the Graduate School from funds supplied by the Wisconsin Alumni Research Foundation.
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[6] Supplied by A. D. Mackay, Inc., New York.